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A Decision Support System for Water Allocation on the Rio Conchos Basin, Mexico

Stewart

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A decision support system for water allocation on the Rio Conchos basin, Mexico.

Steve Stewart (UA), Juan Valdés (UA), Jesus Gastelum (UA), David Brookshire (UNM), Javier Aparicio (IMTA), Jorge Hidalgo (IMTA), Israel Velazco (IMTA)

1. Introduction

Transboundary watersheds such as that of the Rio Grande/Rio Bravo (RGRB) along the US/Mexico border face many obstacles to effective management. An ongoing drought in the region has led to water deliveries from Mexican tributaries to the RGRB system insufficient to meet international obligations. U.S. water interests claim that international treaty obligations should have priority over domestic water uses. Mexico claims that its citizens' needs come first, especially in times of low water availability.

Coupled with the disparate needs of the two nations is a lack of understanding of the cause and effect relationships between policy options, changes in reservoir management and their effects on the river system in this semi-arid environment. To address these needs, we develop a decision support system (DSS) designed to provide water managers with information on the complex effects of reservoir operations and water allocations. We focus our efforts on the largest tributary to the RGRB, the Rio Conchos, which flows largely through the state of Chihuahua, Mexico. The ultimate goal is to develop a DSS that covers the entire RGRB.

The DSS is comprised of a semi-distributed regional system dynamics model (SD) operating on a daily time step that tracks water deliveries and crop production coupled with input-output relationships to generate measures of economic impacts due to reservoir operations for the Conchos Basin in Chihuahua, Mexico. We use the model to obtain estimates of the economic impacts of policies designed to provide larger downstream deliveries needed for Mexico to satisfy its water delivery obligations under the Treaty of 1944.

2. Background

Treaty of 1944

In response to rapid development of the RGRB region in Mexico and the U.S. State of Texas during the early part of the 20th century, differing institutional structures in the two nations, and variability of runoff led to frequent conflicts over water, a The Treaty of 1944 was negotiated between Mexico and the United States. The Treaty divided the waters of the RGRB system flowing between Fort Quitman, Texas and the Gulf of Mexico based on shares of runoff of the rivers. The Treaty was designed to ensure that each nation had access to adequate water in drought years. The Treaty divides the waters of the RGRB equally while simultaneously requiring Mexico to deliver an average of 431 Hm^3 per year over a 5-year period (TCPS 2002).[1] One provision of the Treaty allows Mexico to deliver less than 431 Hm^3 per year in cases of "extraordinary drought" as long as the deficit is made up in the following 5-year cycle. What constitutes "extraordinary" is not explicitly defined in the treaty. Interests on the U.S. side have interpreted it to mean that flow from Mexican tributaries must cease entirely for an extraordinary drought to have occurred (TCPS 2002).

[1] In addition, the treaty authorized the joint construction of Falcon and Amistad reservoirs on the lower Rio Grande and created a requirement that the U.S. deliver 1,850 Hm3 per year of water to Mexico from the Colorado River.

Difficulty in meeting treaty obligations

Mexico has delivered an average of 550 Hm^3 $year^{-1}$ from all tributaries to the Rio Grande/Rio Bravo (RG/RB) from 1944-1996. This represents 127 % of the minimum annual volume required under the Treaty.[2] Of the six Mexican tributaries to the RGRB, the Conchos has historically provided the largest deliveries to the RGRB with a volume of 54% of the total. However, the drought of the 1990s-present has severely decreased releases to the US. From 1992 – present, Mexico has accumulated a deficit of 1728.3 Hm^3 or about 4 years of required annual volume. Mexico has been in deficit during only two other periods: 1953-1958 and 1982-1987. In each of those cases, Mexico provided sufficient additional water during the following five-year period to erase its deficit.

The use of average deliveries as a metric masks the variability of streamflow in this semi-arid region. For example, while average deliveries to the US from the Conchos from 1946-1996 were about 377 Hm^3, the variance has led to many years of deliveries significantly lower than the average required by the Treaty. For example, 1994-1996 releases were less than 200 Hm^3 and 1972 was less than 50 Hm^3.

Historical information

The Conchos River basin is located in the state of Chihuahua in the northern part of the Mexican Republic. It is bordered to the north by the United States and to the east, west and south by other Mexican river basins (Figure 1). The Conchos basin is one of seven hydrological subregions in the Mexican side that integrate 14 hydrological subbasins that form the Rio Grande basin.

The Conchos basin has an area of 64,000 km^2, which represents 14% of the surface area of the Rio Grande Basin. Irrigated agriculture has historically been the major user of water and irrigated acreage continues to expand, but it faces increasing competition from industrial development, maquiladoras, and increasing residential water demand. Agricultural use accounts for approximately 92% of the total surface and groundwater supplies, residential use of the 1,013,378 domestic users in the principal cities accounts for 6.4%, and the remaining consumption is industrial.

Average annual precipitation in the Conchos region is 420.11 mm, much of which falls at elevations greater than 2000m in the Sierra Madre Occidental headwaters. Naturalized annual runoff for the period 1954- 2001 was 2612.5 Hm3.

While agriculture only accounts for about 11% of Chihuahua's economic activity, it employs about 20% of its citizens and is the largest crop producing area in Mexico. Over the last 30 years, an average of 76,000 Ha per year of land has been under cultivation, which has produced revenues averaging US $62,000,000 per year.[3] The temperate semi-arid climate allows for three distinct growing seasons: Spring-Summer (oat, wheat and onion), Fall-Winter (Cotton, Corn and Sorghum), and the year round perennial season (Alfalfa and Vines).

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[2] The average is exaggerated by extremely high runoff in several years that could not be captured with the existing infrastructure.

[3] In 2001 dollars using average prices from 1989-2001 and an exchange rate of 10.0 pesos per U.S. dollar.

Figure 1. Rio Conchos Basin, Mexico (Houston Advanced Research Center, 2000).

With the general expansion of irrigated acreage in the Conchos basin over the last twenty years, irrigated agriculture now uses an average of 1632.85 Hm^3 of surface water per year and 904.00 Hm3 of groundwater, which represents 97.66% of the total demand for water in the region. Three irrigation districts with a combined irrigated acreage of 95,154 ha compose this sector. In addition, there are numerous smaller irrigation units distributed along the basin with a total irrigated area of 83,328 ha of which 14,509 ha are irrigated with surface water. The irrigation districts are characterized by low water efficiencies, which are around 40%, while the smaller irrigation units' efficiencies are about 48%.

Table 1- Historical crop production

	Surface (Ha)		Data Yield		Crop Prices	
Crop	Cultivated	Harvested	Yield (ton/ha)	Total Yield (ton)	($ ton) Average from 1989-2001	Tot revenue ($ USD)
Total	77653.81	76553.87	11.35	607851.46	$195.00	$62,029,843
Oat	1005.07	999.89	13.27	7793.30	$76.46	$321,123
Cotton	5520.74	5400.63	2.98	15795.08	$275.33	$7,423,390
Perennial	14018.96	13584.74	5.92	151799.22	$313.22	$13,805,066

3. The Decision Support System

The decision support system (DSS) we present here is based on the fundamental ideas of system dynamics (SD), first developed by Forrester (1961). SD is a way to represent a process as a series of interdependent stocks and flows (Forrester 1969). SD allows the study of timedependent systems that have complex feedback mechanisms such as those in groundwater/surface water systems having multiple uses. System dynamics is basic to our understanding of how the hydrological cycle interacts with natural and human influences such as social, cultural, economic, political and institutional factors by tracking the linkages between them over time.

Because of the importance of the Conchos Basin to interests within the RGRB, an SD model that accurately captures the relationships between precipitation, irrigation withdrawals, crop choices, and reservoir operations is needed. The SD model was packaged within a DSS and created with the purpose of representing the current and feasible future states of the hydrologic system of the basin, its dynamics, the response of the system to climatic variability and examining the effects of structural changes in water delivery, application, demand, or institutional constraints.

The DSS presented here is designed so that water resource planners and state level policy makers can have an intuitive understanding of the implications of various water management strategies on the Conchos, and in particular point out potential areas for optimization of reservoir storage and delivery policies. If designed effectively, the DSS can serve to inform policy decisions to develop the Conchos region in a sustainable manner while meeting the requirements of the 1944 Treaty.

Model features

The SD model is structured on three principal submodels and an extension to capture economic impacts: a) The precipitation-runoff submodel is based on the U.S. Soil Conservation Service curve number method, which estimates runoff given precipitation and the physical characteristics of the basin. An 80-year time series of monthly precipitation data was incorporated into a simulation routine to generate daily precipitation. Daily precipitation was obtained by multiplying the monthly precipitation values by daily weights for the different months of the year. The following procedure was used to estimate the daily weights: 1) Select the most representative gage of each Conchos subbasin by considering factors such as mean precipitation, gage location, etc. 2) For the selected gage in each subbasin, analyze and estimate the average historic rainy days for each month. 3) Select the year of historic precipitation data that has the closest fit of number of rainy days to the average estimated in 2 above. 4) Using the yearly data selected in 3, estimate the daily weights for each month. For example, if the number of days in January in which ran fell were 10, they daily weights would be 1/10, such that the amount of monthly precipitation would be evenly divided across those 10 days. Each January in the 80 year run would have the same precipitation profile. Similarly for the other months of the year. The calibrated synthetic runoff results are consistent with historical sub-basin runoff. Much time was invested in order to be sure that the SCS in conjunction with the daily soil moisture balance were behaving adequately. Each scenario uses the same runoff profile.
b) The agricultural water use and crop yield model, which determines crop water requirements, is based on the Daily Soil Moisture Balance Method (DSMBM). The DSMBM calculates the water required during different phases of growth and for each crop modeled. Given precipitation infiltration, potential evapotranspiration (PET) and the knowledge of the field capacity and wilting point, the DSMBM allows estimation of actual evapotranspiration, water percolation to the aquifer and irrigation water requirements for each of the crops. Each of the representative crops – Oats, Cotton, and Perennials has a unique requirement. Crop yield is determined through

the use of the daily relationship equation between crop yield and relative evapotranspiration (Flinn 1971, Hidalgo 1984).
c) The reservoir-operation model, which simulates mass balance of the reservoir in relation to inflows and outflows.
d) A set of input-output multipliers that represent the direct and indirect effects of changes in crop revenues on the overall basin economy.

4. Policy Scenarios

The principal water problems on the Conchos basin are related to prolonged drought, episodic storm events and inefficient water use. We simulate the effects of different management strategies for the same precipitation profile over an 80-year period. While it is difficult to determine the exact management strategy or strategies employed by the Mexican Comision Nacional del Agua (CNA), the six scenarios we examine were designed to capture some simple operation strategies having varying levels of priority for irrigation and Treaty obligations. Each of the numerically increasing scenario numbers represents decreasing priority on meeting US water delivery requirements and increasing flexibility to deliver water to agricultural interests in Mexico.

Scenario 1: Daily US delivery target. The baseline represents our base case water management scenario. This naïve policy aims to meet the 300 Hm^3 per year requirement for the Conchos by delivering a constant daily quantity of water (.821 Hm^3) to the US. Only after US obligations are met is irrigation water made available to Mexico. Any daily deficit is made up from excess water available in subsequent days.

Scenarios two and three represent somewhat traditional reservoir operation polices where reservoir releases are based on a set of guide curves that determine the appropriate release given a specific reservoir level or time of the year.

Scenario 2: Reservoir forecast. In scenario 2 a simple linear relationship between minimum reservoir level and maximum level determines releases. The minimum release is zero when the reservoir is at or below its minimum capacity and the maximum is twice the constant daily volume considered in scenario 1. In this case, there is a target release of (.821 Hm^3) to satisfy the Treaty, however, if following the linear guideline results in less than .821 Hm^3 being delivered on a given day, the deficit is not considered on subsequent days.

Scenario 3: Reservoir forecast (conservative). Identical to scenario 2 except that a guide curve that reduces releases at low reservoir volumes is used.

Scenario 4: Reservoir/precipitation forecast. Scenario 4 is similar to scenario 2 with the addition of a precipitation forecast. The forecast acts as a multiplier to release additional water if the ratio of cumulative precipitation to average historic precipitation at any point in the year is greater than one, or less water if the ratio is less than one.

Scenario 5: Reservoir/precipitation forecast (conservative). Identical to scenario 4 except that a guide curve that reduces releases when reservoir volume is low is used.

Scenario 6: Spills only. There are no explicit water releases to meet the Treaty. Irrigation in Mexico has first priority. Only water beyond the capacities of the reservoirs and return flow from agricultural operations is delivered to the U.S.

5. Discussion

Scenario results

The model is largely consistent with observed system behavior. Agricultural production and water releases to the US are perhaps the two main outputs that one would hope the model would be able to predict reliably. It appears from a cursory inspection of model's output with historic crop production that the model may overstate crop production and water deliveries as in each of the six cases modeled as water deliveries to the US are higher than the 299.2 Hm^3 historical average and crop values are much higher. We believe that there are two main reasons for the differences: First, increased average water delivery is due largely to decreased crop water requirements in the irrigation sector of the model relative to the 1600 Hm^3 per year delivered over the last decade. Second, cultivated acreage, crop prices, and the value of the Mexican peso have fluctuated dramatically over the last decade.

The model allows the calculation of daily irrigation water requirements given alternative irrigation policies. In our six scenarios, soil moisture must be equal to or greater than 80% of soil field capacity, which produces smaller irrigation depths than the average historic depth of the last 10 years for each of the 3 irrigation districts. Consequently, the 109,629 ha of irrigable acreage in the model requires a range of application from 1164 Hm^3 in Scenario 1 to 1605 Hm^3 in Scenario 4, while average irrigated acres during the last ten years was 75,018 ha and required 1597 Hm^3 per year. Because the model predicts lower water usage for the irrigated acreage and crops produced than is found in the historical record, more water is available downstream.

Agricultural production in the Conchos region is highly variable. Regional crop prices, even across the three irrigation districts, have large fluctuations. In addition, exchange rate issues, especially after the devaluation of the peso, have had a large effect on the incentive to produce crops, and the prices received for them.[4] Finally, historical crop production decisions may have been a result of social or environmental conditions that are not considered in the model.

Deliveries to the U.S.

Average deliveries to the US are reported in Table 3. In each of the six cases, *average* deliveries over the 80-year simulation period exceed the 299.2 Hm^3 historic release. However, the averages mask the often-large fluctuations in deliveries to the U.S. In all but Scenario 1, deliveries fall below 300 Hm^3 in more than half of the years in the 80-year runs.[5] In the extreme case, Scenario 6 leads to adequate water in only 28 years of the 80-year cycle.

If one were to consider five-year cycles, as does the Treaty, the performance of Scenario 1, like the historical record, leads to three periods similar to the 1992-2003 period.[6] Scenarios 2 and 4 leads to deficit in 31% and 37% of 5-year cycles, while Scenarios 3 and 5 lead to deficit in 50% and 43% of cycles. Scenario 6, which arguably represents an extreme strategy for Mexico,

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[4] For example, in 1994 one U.S. dollar would buy four pesos. By 2003, the same dollar would buy ten pesos.
[5] In each of the scenarios which are based on the same precipitation data from the historical record, several extremely wet cycles distort the averages.
[6] The five-year cycles defined in the Treaty begin when the downstream reservoirs reach a certain capacity. Because our SD model does not consider reservoirs on the RGRB, we use the arbitrary starting date of 2004 and consider subsequent 5-year periods from then until 2084, the end of our model run.

leads to deficits in 68% of cycles. It should be noted that the Scenarios behave very similarly in medium to high precipitation years.
Low precipitation years tend to exacerbate the inability to meet fixed delivery requirements such as the 300 Hm^3 threshold expected in the treaty.[7]

Figure 2 illustrates the disparity provide an illustration of Scenarios 1 and 6, the two extremes of our study scenarios. Relative to Scenario 1, in Scenario 6 the means of the deliveries have changed only slightly, but the distribution has much more mass below the critical threshold of 300 Hm^3. The results emphasize that it is the low precipitation years and in particular, cases where multi-year drought exhausts the ability to meet water demands through reservoir storage that have led Mexico into series of recent water deficits to the US.

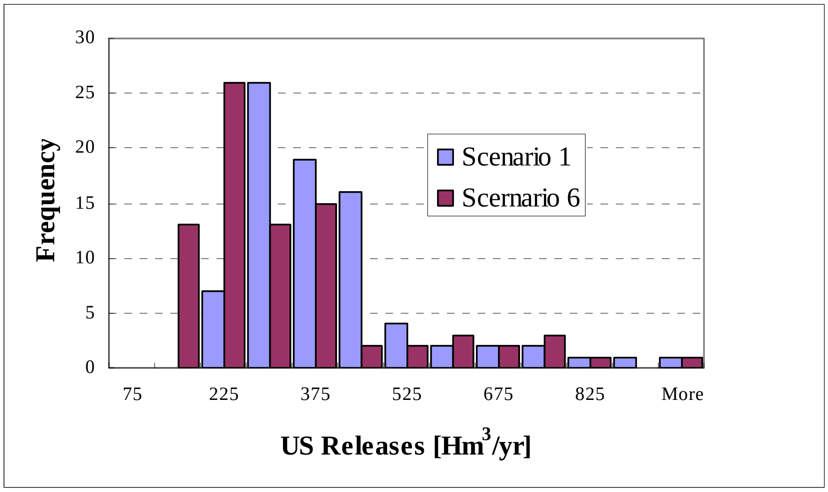

Figure 2 – Distribution of treaty deliveries

Mexican economic impacts

Table 3 reports the average annual irrigation water available for Mexican crop production as well as average crop yield and annual crop revenue for the six scenarios.[8,9] Upon examination, it is clear that perennial crops such as grapes, pecans, and alfalfa benefit most from the additional irrigation water available under Scenarios 2-6, while oats has the least variance between the six scenarios.

The net present value of annualized production for the 80-year simulation is presented in Table 3. When considering Scenario 1 as the baseline, the five scenarios represent a range of

[7] The Colorado Compact between upper and lower basin states along the Colorado River in the Southwestern U.S. is another example of a fixed delivery requirement. The Compact, which divided Colorado River water roughly evenly between the upper and lower basin states, requires the upper basin states to deliver a fixed quantity of water to the lower basin states. The quantity agreed upon was roughly half of the flow of the river, but the flow was measured in a series of above average runoff years.
[8] Figures are calculated using represent idealized, but feasible irrigation efficiencies, constant 2001 prices and an exchange rate of 10 pesos to the dollar, reflecting 2003 conditions. In addition, we assume to change in irrigable acreage over the 80-year time horizon.
[9] Again the reporting of average annual crop production and values masks the large fluctuations in production that occur with highly variable water availability.

increased Mexican agricultural output from a low of 14% for Scenario 2 to a high of 25% for Scenario 6.

Zárate-Hoyos (2001) reports agriculture sector multipliers from a structural accounts matrix to be in the range of 1.48 – 2.14. Using the lower bound figure of 1.48, the gain in total economic activity in Mexico between Scenarios 2-6 and the baseline Scenario 1 ranges from $29.5 million for Scenario 2 to $52.2 million for Scenario 6. The marginal value of water implied from our scenarios is consistent with the values reported by others in the RGRB region. Robinson (2001) reports that for each acre-foot of reduced flows to the RGRB, counties in Texas face $652 in economic impacts. Our model implies economic impacts in Mexico ranging from a low of $268 per acre-foot in Scenario 3 to a high of $425 per acre-foot in Scenario 2. The lower values per acre-foot in Mexico are not surprising given the generally low water use efficiencies in the region.

The disparity in value between Mexico and Texas raises an interesting question. If water could be marketed across borders such that Mexican citizens could be compensated for water deliveries beyond those required by the treaty, Texas irrigators, in principle, would be willing to purchase additional water for more than it is worth to Mexican irrigators. Assuming all payments from Texas to Mexico were spent on goods and services in the Mexican economy, these water markets would lead to gains for both Chihuahua, Mexico and the US state of Texas and lead to increases in economic efficiency in the region.

6. Conclusions

The DSS presented here provides a tool that is useful for analyzing the impacts of alternative international water allocation schemes, climate change, drought, changes in irrigation technology, as well as increasing municipal and industrial demands. Aside from the obvious utility of providing economic measures of the impacts of reservoir management strategies, the model helps illustrate why SD models can be so useful in water resources management. Without the dynamic feedback loops that are incorporated in the model, it is likely that some of the important properties of the system would be ignored. For example, increases in early season application of irrigation water
via increases in soil moisture depths can actually lead to decreases in crop production in low water years because sufficient water may not be available later in the season to satisfy the increased depth.

While we were interested in exploring alternative means of meeting international treaty requirements, the model can be used for the more mundane issues that water managers are often interested in exploring such as simulating transfers between reservoirs, examining evaporation in low vs. high elevation reservoirs and changes in conveyance losses.

Future versions of the model will allow reallocation of water between irrigation districts and allocation to a broader selection of crops. This will allow investigation of water markets within Mexico. A model that allows water to be marketed is almost certainly going to lead to increases in efficiency for the region, whether efficiency is defined as increased economic activity, additional acres irrigated, or minimization of water waste. Eventually the model will be linked to others being developed for the RGRB on the U.S. side.

Table 2 Selected model outputs. Values 2001 US dollars.

	Delivery to US (Hm^3)					
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
avg	380	357	341	353	337	307
std. dev.	256	260	262	277	272	289
			Avg Irrigation Water (Hm^3)			
avg	1165	1449	1508	1465	1520	1605
			Annual mean crop yield (ton)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Oats	15799	16191	16279	16262	16324	16409
Cotton	134161	142833	148031	143755	149332	159709
Perennial	177564	204458	212226	205158	212688	222354
			Annual mean crop revenue (USD)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Oat	$2,915,941	$3,002,399	$3,021,807	$3,018,144	$3,031,692	$3,050,633
Cotton	$31,028,802	$33,251,607	$34,371,105	$33,465,883	$34,672,293	$36,903,203
Perennial	$109,004,543	$126,691,471	$131,735,934	$127,157,081	$132,045,807	$138,323,277
All Crops	$142,949,285	$162,945,477	$169,128,847	$163,641,108	$169,749,792	$178,277,113
			Net Present Value - Annualized			
Annualized NPV	$2,033,025,515	$2,317,411,462	$2,405,351,380	$2,327,304,734	$2,414,182,466	$2,535,458,065

Table 3 - Economic Impacts

Economic impact compared to Scenario 1 baseline (USD)					
	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6
Impact	$29,594,364	$38,745,751	$30,623,898	$39,664,750	$52,285,184

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Author contact information:

Steven Stewart
Department of Hydrology and Water Resources/SAHRA
The University of Arizona
Tucson, AZ 85721-0011
(520) 626-3892
sstewart@hwr.arizona.edu